Nanotechnology: From Imagination to Reality

Imagine a single area of scientific discovery with the potential to enable a wealth of innovative new technologies across a vast array of fields including healthcare, information technology, energy production and utilization, homeland security and national defense, biotechnology, food and agriculture, aerospace, manufacturing, and environmental improvement. Nanoscience, the study of the unique properties of matter that occur at extremely small scales, has this potential.

Advances in nanoscience and nanoengineering are already ushering in new applications—or nanotechnologies—that are leading to improved products across a broad realm of sectors, from textiles to electronics. Some of these improved products are already available, including improved catalysts, stain resistant fabrics, better sunscreens, superior dental bonding materials, high resolution printer inks, digital camera displays, and high capacity computer hard disks, to name a few.

In addition to making existing products and processes better, nanotechnology promises breakthroughs that will revolutionize the way we detect and treat disease, monitor and protect the environment, produce and store energy, and build complex structures as small as an electronic circuit or as large as an airplane. For example, microscopic devices small enough to be carried in the human bloodstream may someday monitor the body for early signs of disease and deliver treatments that are targeted to the appropriate cells of the body. Exquisitely sensitive and selective sensors could be deployed in uses ranging from environmental stewardship to food safety to homeland security. And materials with superior characteristics—many times stronger than steel but a fraction of its weight, for example—could be used to build better cars, planes, spacecraft, buildings, and creations we have yet to imagine. Clearly, nanotechnology has the potential to profoundly change our economy, to improve our standard of living, and to bring about the next industrial revolution.

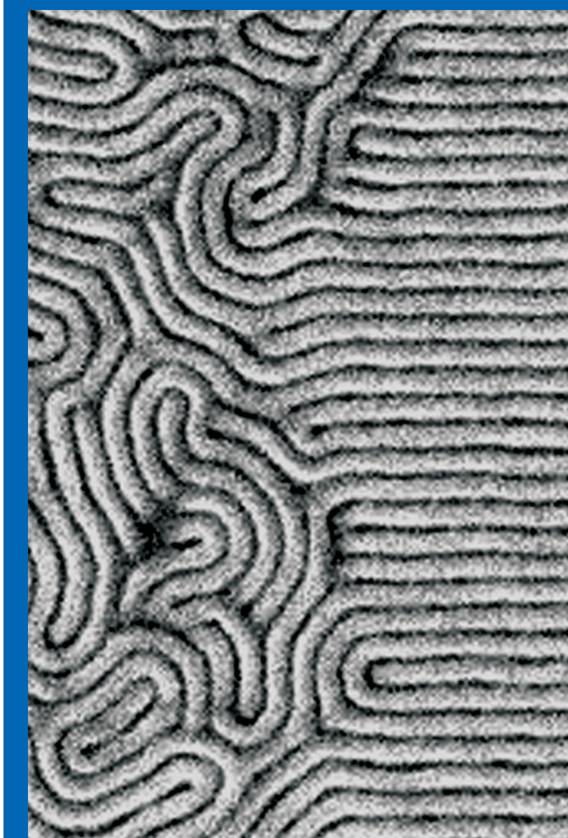

Figure 1. Scanning electron-microscope image of top edges of thin sheets of polystyrene and polymethyl-meth-acrylayte. The ordered arrangement of the stripes , each about 24 nm wide, on the right was generated by a striped nano-pattern on the substrate surface. The left part of the substrate was unpatterned (courtesy P.F. Nealey and S.O. Kim, University of Wisconsin).

The scientific discoveries that will enable these breakthroughs entail more than simply the miniaturization of existing technologies. Nanoscale science, engineering, and technology, collectively referred to as nanotechnology, define research and development (R&D) aimed at understanding and working with—seeing, measuring, and manipulating—matter at the atomic, molecular, and

Recent achievements in nanotechnology funded in whole or in part by the National Nanotechnology Initiative

- Use of the bright fluorescence of semiconductor nanocrystals (quantum dots) for dynamic angiography in capillaries hundreds of micrometers below the skin of living mice—about twice the depth of conventional angiographic materials and obtained with one-fifth the irradiation power.
- Nano-electro-mechanical sensors that can detect and identify a single molecule of a chemical warfare agent—an essential step toward realizing practical field sensors.
- Nanotube-based fibers requiring three times the energy-to-break of the strongest silk fibers and 15 times that of Kevlar fiber.
- Nanocomposite energetic materials for propellants and explosives that have over twice the energy output of typical high explosives.
- Prototype data storage devices based on molecular electronics with data densities over 100 times that of today's highest density commercial devices.
- Field demonstration that iron nanoparticles can remove up to 96% of a major contaminant (trichloroethylene) from groundwater at an industrial site.

supramolecular levels. This correlates to length scales of roughly 1 to 100 nanometers. At this scale, the physical, chemical, and biological properties of materials differ fundamentally and often unexpectedly from those of the corresponding bulk material. Nanotechnology R&D is directed toward understanding and creating improved materials, devices, and systems that exploit these fundamentally new properties, phenomena, and functions. An example of the type of nanoscale structures that can be grown by highly controlled fabrication processes is shown in Figure 1.

With any new and disruptive technology, and particularly one that has significant potential for extremely broad impact, there will be societal and ethical implications. Understanding these implications and ensuring that their consideration is integrated with the development of the technology is vital to achieving the maximum societal benefit. The Federal R&D program includes societal and ethical implications as one of its principal elements.

In order to coordinate the multiagency Federal R&D program in nanotechnology, the National Nanotechnology Initiative (NNI) was established in FY 2001. The goals of the NNI are to: (1) conduct R&D to realize the full potential of this revolutionary technology; (2) develop the skilled workforce and supporting infrastructure needed to advance R&D; (3) better understand the social, ethical, health, and environmental implications of the technology; and, (4) facilitate transfer of the new technologies into commercial products.

The National Nanotechnology Initiative: Fueling Innovation...

... By Improving Fundamental Understanding

The state of nanotechnology today represents something of a paradox. On the one hand, new products using nanotechnology have been developed and are in the marketplace. On the other hand, understanding of the underlying properties of nanoscale materials and structures is still at a rudimentary level. Many existing models for explaining material, device, and system behavior do not extrapolate to the nanoscale regime. In order to maximize the development of future innovations, a significant portion of the NNI investment is directed toward basic research to achieve a fundamental understanding of nanoscale properties and processes.

Basic research, even when aimed at a specific problem, can lead to surprising new results. Such surprises frequently are the bases for the most innovative technological advances. Therefore, a broad-based, balanced, knowledge-oriented research investment is crucial not only to advancing the frontiers of science, but also to realizing the full economic potential of nanotechnology. The surprising discoveries and new research tools that result from investment in nanotechnology research will undoubtedly have far-reaching impacts in other fields of science and engineering as well. Many agencies such as NSF and DOE have a focus on support for fundamental research.

As it has in the past in areas such as information technology and biotechnology, investing in basic research in nanotechnology is expected to lead to significant, new economically valuable technologies. However, the time to take a concept developed through basic nanotechnology research to a commercial product is beyond five or even ten years—or, for truly fundamental research, may be altogether unknown. Therefore, private investors are not generally in a position to provide the necessary financial support. Because nanotechnology is of such critical import to U.S. competitiveness, both economically and technologically, even at this early stage of development, it is a top priority within the Administration's R&D agenda.

... By Focusing on Applications

A broad, balanced basic research program both complements and supports more focused work aimed at incorporating scientific discoveries into innovative technologies. Many agencies such as DOD, DOE, EPA, NASA, NIH, NIST, and USDA support applied research aimed at developing technology related to the agency's mission. Federal investment in a combination of fundamental and applied research will move novel concepts closer to applications that are useful for both government and commercial purposes.

... Through Multidisciplinary Collaborations

Another aspect of nanotechnology R&D worth noting is the key role played by multidisciplinary and interdisciplinary efforts. That is, advances will be built upon progress in more than one area of research or on truly collaborative interactions among researchers from various disciplines. A key component of the NNI is coordination of the Federal investment and strengthening of intra- and interagency efforts fostering multidisciplinary research.

... By Facilitating Technology Transfer

At this early stage, an important mechanism by which nanotechnology can find its way into commercial applications is through interaction among industry, academic, and government researchers. Such networking and partnering is facilitated and encouraged under the NNI by the establishment or support of centers, networks, and facilities that are available to researchers from all sectors. Examples include the existing National Nanofabrication Users Network (NNUN) and a suite of Nanoscale Science Research Centers (NSRCs), each with a specific focus, to be colocated at Federal laboratories across the country. Interaction among researchers from various sectors is also facilitated under the NNI through the organization of topical workshops.

Additionally, small businesses, which are frequently at the forefront of the development of new, high technology products, can receive support through the agency-run Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs directed specifically at nanotechnology-based solutions. A goal of all of these efforts is to expedite knowledge transfer and, ultimately, to facilitate commercialization of nanotechnology. By addressing measurements, standards, and manufacturing directly in the grand challenges, the NNI is ensuring that the appropriate infrastructure is developed to facilitate the rapid commercialization of laboratory successes.

... For Enhanced U.S. Competitiveness

The United States is not the only nation to recognize the tremendous economic potential of nanotechnology. While difficult to accurately measure, some have estimated that worldwide government funding has increased to about five times what it was in 1997, exceeding $2 billion in 2002.[1] In the United States, the Federal investment in nanotechnology R&D has increased from $116 million in FY 1997[2] to a request of $849 million in FY 2004. In order to realize nanotechnology's full potential and to maintain a competitive position in the worldwide nanotechnology marketplace, the Federal Government's investment will continue to play a critical role in accelerating scientific discovery and nurturing new technologies and fledgling industries.

... Responsibly

Since the inception of the NNI, assessing the implications of the technology has been an integral part of the planning and programs of the Initiative. Research on implications for human health, society, and the environment is increasingly being emphasized as tangible new nanostructures and nanomaterials are discovered and new nanotechnology products are developed. The results of such research are being taken into consideration by those Federal agencies whose work is directed at regulatory issues.

[1]M.C. Roco. 2002. "International Strategy for Nanotechnology Research and Development," *Journal of Nanoparticle Research,* Kluwer Academic Publishers, Vol. 3, No. 5-6, 2001, pp. 353-360, as updated April 5, 2002: http://nano.gov/intpersp_roco.html.

[2]R.W. Siegel et al. 1999. *Nanostructure Science and Technology,* Kluwer Academic Publishers, Chapter 8, p. 133: http://www.wtec.org/loyola/nano/08_01.htm.